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REDISTRIBUTION OF ELEMENTS IN THE FORMATION OF SEDIMENTARY ROCKS[1]

WARREN J. MEAD

PROBLEM

Sedimentary rocks are derived from the destruction of older rocks—igneous, crystalline, and sedimentary. The pre-existing sedimentary rocks may themselves have come from still earlier sediments, and these in turn from earlier ones, and so on back, but ultimately their derivation may be traced to the igneous and crystalline rocks, the latter term being used to include schists and gneisses resulting from the metamorphism of the igneous and sedimentary rocks, and others whose origin cannot be determined. Obviously igneous rocks, and the crystalline rocks of the Archean or Basement Complex, whatever their origin, have yielded the materials for all later sediments, some of which have gone through several cycles of erosion and redeposition.

The development of a sedimentary rock from an igneous or crystalline rock involves redistribution of the materials, both minerals and elements. In the process of weathering, certain materials are taken into solution, while others are not. Of the materials not dissolved, some are removed by erosion as finely divided rock particles—mud, silt, and sand. The remainder consists of the partially weathered rock and residual clays which remain *in situ* where erosion lags behind such alteration.

The material transported in a solid state, upon deposition, forms the mechanical sediments of shales, sandstones, etc. Of the material carried in solution, a portion is deposited as cementing and vein-filling materials during the process of transportation. After reaching the sea, a part of the remaining material is precipitated, forming the chemical and organic sediments, the limestones, and other carbonates;

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[1] This is the first of a series of articles on metamorphic problems to come from the Metamorphic Laboratory of the University of Wisconsin. The next title will be "The Metamorphic Cycle," by C. K. Leith.

and what is not precipitated remains in solution as part of the mineral matter of the sea.

The following table shows the general plan of redistribution:

TABLE I

General Plan of Redistribution

Original Rock	Material removed	Carried as solids	Mechanical sediments (shales, sandstones, etc.)
		Carried in solution	Chemical sediments (limestones, etc.) Cementing materials Vein-filling materials Mineral matter of the sea
	Material remaining	....	Weathered rock Residual clays or earth

Various attempts have been made at quantitative estimates of the redistribution above outlined. Figures for the total thickness and relative amounts of the three classes of sediments have been obtained from actual measurement, but such estimates are confined to the present continental areas, taking no account of suboceanic deposits, and are limited to the comparatively small areas which have been studied by geologists. Several estimates have been made based on the nature and amount of material being carried to the sea by rivers, particularly on the ratio of calcareous to clastic sediments formed.

A few estimates have been made based either in part or entirely on chemical evidence. One of these has been made by Van Hise,[1] who has determined the relative amounts of shale, sandstone, and limestone on the basis of observed thickness, combined with chemical considerations, to be 65 : 30 : 5. Average chemical analyses of the shales, sandstones, and limestones were combined in the ratio of 65 : 30 : 5, respectively, and the resulting combination was found roughly to approximate the composition of the average crystalline rock.

A more recent estimate of the same ratio is one made by Clarke,[2] based on chemical evidence. This estimate is discussed on a later page.

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[1] C. R. Van Hise, *A Treatise on Metamorphism*, Monograph No. 47, U. S. Geological Survey, 1904, chap. xi.

[2] F. W. Clarke, "The Statistical Method in Chemical Geology," *Proceedings of the American Philosophical Society*, Vol. XLV (1906), p. 21.

In the present paper the redistribution of the elements of the original crystalline rock will be taken up from a purely chemical standpoint. It will be the purpose to determine in what proportions the various sediments should be combined to yield an average composition most nearly like that of the original rocks from which they were derived, and to point out reasons for discrepancies which may develop.

We may look upon the table given on page 239 as an equation which may be written as follows:

$$\text{Original crystalline rock} + \text{Redistribution agencies} = \left\{ \begin{array}{l} \text{Shales} \\ \text{Sandstone} \\ \text{Limestone} \\ \text{Vein-filling materials} \\ \text{Cementing materials} \\ \text{Salts of the sea} \\ \text{Residual matter} \end{array} \right.$$

If the several end-products making up the right-hand side of the equation could all be taken into account in proportion to their abundance, it is evident that the elements of the original rock would all be accounted for unless some minor factor has been overlooked. Of these end-products fair average chemical analyses are available for shales, sandstone, and limestone, and also for the salts of the sea. Of the vein-filling material very little is known in regard to abundance, and an average chemical analysis is impossible. Better, but still poor, results may be obtained from the residual materials. The cementing material is included in the analyses of the mechanical sediments. The sedimentary rocks form the major part of the mass of the secondary material, the other end-products being only a small percentage of the total mass; hence the proper combination of their analyses should approximate the original rocks—i. e., the left-hand side of the equation—even if the less important end-products be not counted, though their omission will cause certain discrepancies. Thus we may expect to find a deficiency of iron, owing to its segregation in iron formations and iron-ore deposits, which are not included in the analyses of the sediments. We may expect to find a deficiency of sodium, owing to the large amount of that element in solution in the sea.

Our purpose, then, is to ascertain in what proportions the sandstones, shales, and limestones should be combined to give the best approximation to the average composition of the original igneous and crystalline rocks, making due allowances for the end-products other than sediments, not included in the combination.

DATA USED

There are only eight of the elements—oxygen, silicon, aluminum, iron, calcium, magnesium, sodium, and potassium—which compose more than 1 per cent. of the outer part of the lithosphere. The least plentiful of these, potassium, makes up about 2.3 per cent. of the lithosphere, while the next element in abundance, titanium, makes up only 0.4 per cent. The present discussion will be confined to the eight most abundant elements, which will be treated in the form of the following oxides: silica, alumina, magnesia, soda, and potassa. Iron will be considered in the metallic form, the sum of the metallic content of the ferrous and ferric oxides being taken in each analysis employed.

Perhaps the best determination of the average crystalline and igneous rocks yet available is one made by Clarke.[1] In obtaining this average the rock-forming elements were considered separately, each being averaged according to the actual number of determinations made. A group of truer estimates was thus secured than by averaging complete analyses together, as he had heretofore done. In the same bulletin (p. 21) are average analyses of the several sedimentary rocks. The average analysis of the shales represents an average of seventy-eight rocks carefully selected and weighted. Two determinations of the average composition of the sandstones are given. The average represents a composite analysis of 624 sandstones, equal weights being taken. For the average limestone Clarke gives two determinations—one a composite analysis of 345 limestones and the other a composite analysis of 498 limestones used for building purposes. For the present purpose an average of the two composite analyses was taken, representing an average of 834 limestones. The several analyses selected are given in Table II.

Most of the mass of the sedimentary rocks is derived from the crystalline rocks, but, in the process of redistribution, water and gases from the hydrosphere and atmosphere combine with the

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[1] F. W. Clarke, *Bulletin No.* 228, U. S. Geological Survey, 1904, p. 17.

"derived" elements, either chemically or mechanically, and thus enter into the constitution of the sediments. These elements *not* derived from the crystalline rocks must be omitted from the analyses of the sediments before any quantitative estimates can be made on the redistribution of the elements of the crystalline rocks. In Table II the "underived" elements are marked with an asterisk, and the sum of the "derived" elements is given below. Omitting the "underived" elements, the analyses are recalculated on a basis of 100 per cent. totals which gives the analyses in Table III.

TABLE II

AVERAGE ANALYSES SELECTED FOR USE IN THE PRESENT DISCUSSION

	Av. Crystalline	Av. Shales	Av. Sandstone	Av. Limestone
SiO_2	60.48	58.38	81.76	9.64
Al_2O_3	15.17	15.47	5.37	1.28
Fe_2O_3	2.61	4.03	1.23	0.65
FeO	3.44	2.46	0.57	....
MgO	4.10	2.45	0.85	6.20
CaO	4.84	3.12	3.28	41.60
Na_2O	3.43	1.31	0.61	0.33
K_2O	2.96	3.25	1.24	0.45
*H_2O	1.89	5.02	1.69	0.97
TiO_2	0.72	0.65	0.33	0.07
P_2O_5	0.26	0.17	0.07	0.23
*CO_2	....	2.64	3.02	35.58
*S, SO, C	....	1.46	0.08	0.15
BaO and MnO	0.10	0.05	....	0.04
Total	100.00	100.46	100.10	100.19
"Derived"	98.11	91.34	95.30	60.49
"Underived"	1.89	9.12	4.80	39.70

TABLE III

"DERIVED" ELEMENTS OF TABLE II RECALCULATED TO 100 PER CENT. TOTALS

	Av. Crystalline Rock	Av. Shales	Av. Sandstone	Av. Limestone
SiO_2	61.60	63.90	85.72	15.94
Al_2O_3	15.47	16.96	5.63	2.12
Fe_2O_3	2.66	4.41	1.29	1.07
FeO	3.51	2.70	0.60	....
Fe	4.60	5.19	1.37	0.75
MgO	4.18	2.69	0.89	10.25
CaO	4.93	3.42	3.45	68.75
Na_2O	3.50	1.44	0.64	0.55
K_2O	3.02	3.56	1.29	0.74

METHODS USED

The problem now is to determine in what proportions the foregoing analyses of shales, sandstone, and limestone (Table III) should be combined so as to give an average analysis as nearly like that of the average crystalline rock as possible. "Cut and try" methods are both tedious and unsatisfactory. A method of solution has been devised by means of which definite results may be obtained and the general conditions of the problem observed in perspective.

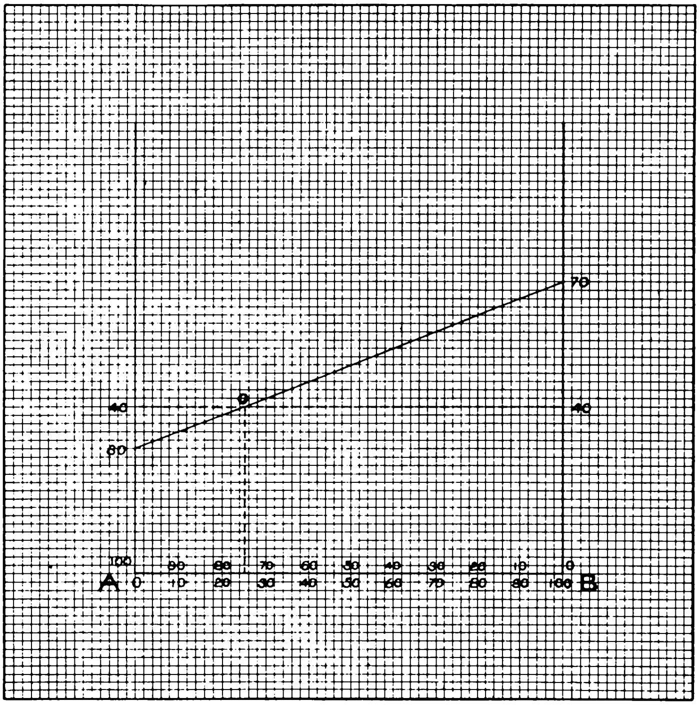

Fig. 1

It will perhaps make an explanation of the method of solution clearer if the general principles are first applied to the simpler case of a combination of two analyses. Suppose, for example, it is desired to find out what proportions must be taken of two rocks, *A* and *B*, having respectively 30 and 70 per cent. of silica, to yield a combination that shall contain 40 per cent. of silica. Vertical distances in

Fig. 1 represent percentages of silica, and the two amounts of silica are plotted on the two vertical lines marked *A* and *B*, and the points connected by a straight line. This line represents by its ordinates the amount of silica in any possible combination of the two rocks, from 100 per cent. of one at one end to 100 per cent. of the other at the opposite end. To find what point on the line represents a combination containing 40 per cent. of silica, a horizontal line is drawn at a distance of 40 units from the base. Now, if the point *O*, at the intersection of the two lines, be projected vertically downward to the base, the percentages of the two rocks in the combination may be read at once; the figures above the base line representing percentages of A and those below the line percentages of *B*. It is seen that the combination is made up of 25 parts of *B* and 75 parts of *A*. In a similar manner it is possible to deal with each element in the rocks.

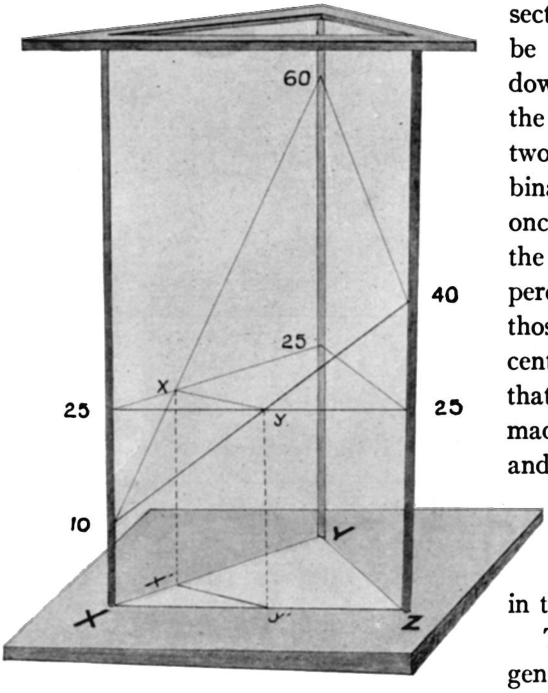

FIG. 2

To apply the same general principle to the case of the combination of three rocks: Suppose, for example, it is desired to ascertain what combination of three rocks, *X*, *Y*, and *Z*, having respectively 10, 60, and 40 per cent. silica, will contain 25 per cent. of silica. It is apparent at once that this problem cannot be considered in two dimensions, as was done in the case of a combination of two rocks; but the same general method may be employed by considering the problem in three dimensions. In Fig. 3 the three uprights are erected perpendicular to the base at the corners of an equilateral triangle. The uprights correspond to the three rocks, *X*, *Y*, and *Z*, and are lettered accordingly. Vertical distances represent percentages of the elements as in Fig. 1. Points on the uprights representing percentages of silica are connected by a plane, instead of a line as was done in the case of the combination of two rocks. The ordinates of this plane represent any percentages of silica which may result from any possible combination of the three rocks. To ascertain what points in the

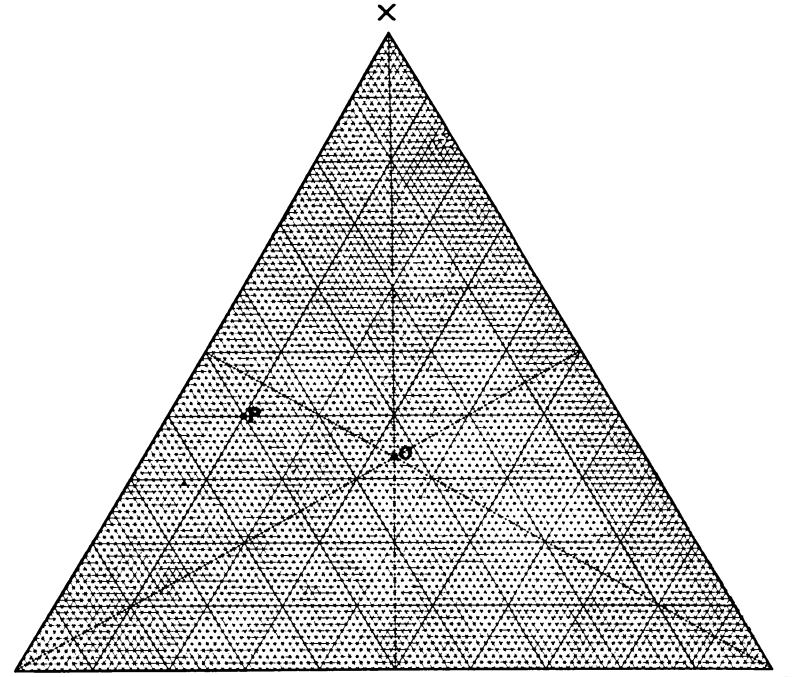

FIG. 3

plane represent 25 per cent. of silica, a plane is passed parallel to the base at a height of 25 units, and the line of intersection of the two planes contains all the points in the first plane which represent the desired 25 per cent. of silica. In the case of a combination of two rocks, as illustrated in Fig. 1, the ratios in which the two rocks entered into the desired combination was determined by projecting the point of intersection of the two lines onto the line at the base. In the case of a combination of three rocks, we have a triangular surface at the base instead of a line. For this triangular surface a piece of triangular cross-section paper is used, like the one shown in Fig. 3. The three corners represent respectively 100 per cent. of *X*, 100 per cent. of *Y*, and 100 per cent. of *Z*. Any point in the triangle represents some combination of *X*, *Y*, and *Z*, and the percentage of each in the combination is measured by the distance

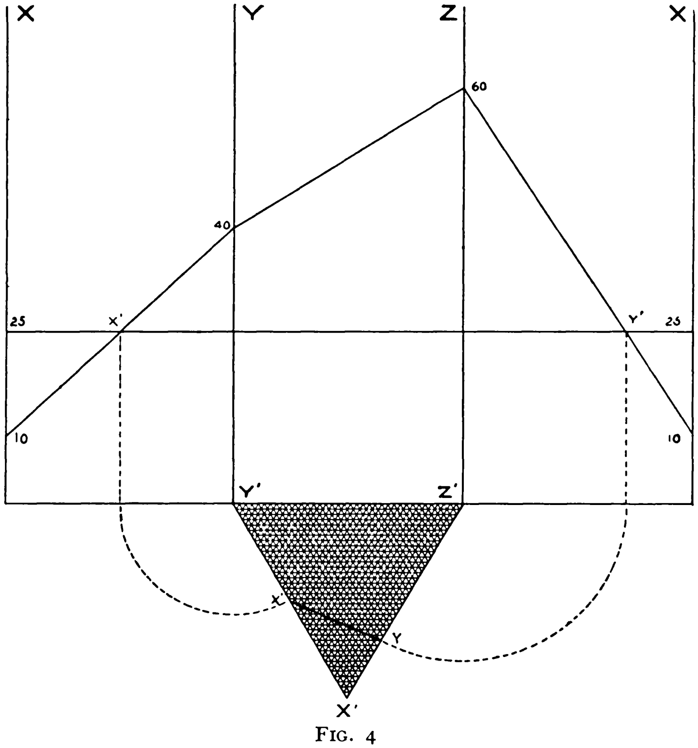

FIG. 4

between the point and the side opposite. To illustrate: the point P represents a combination made up of 40 per cent. *X*, 50 per cent. *Y*, and 10 per cent. *Z*. The point O in the center of the triangle represents a combination containing 33⅓ per cent. of each of the three.

If the line of intersection of the two planes in Fig. 2 be projected vertically downward onto the base, it will represent all possible combinations of *X*, *Y*, and *Z* which contain 25 per cent. silica. By the same process the planes for the alumina content of the rocks may be drawn and the line of intersection projected onto the base. This line will indicate all combinations of the three rocks which contain a certain percentage of alumina. The point of intersection of the silica line and the alumina line on the cross-section paper at the base indicates what combination of the three rocks contains the same amounts of silica and alumina as a given fourth rock. That is, we have found out in what ratios *X*, *Y*, and *Z* must be taken to give a combination having the same content of silica and alumina as a given fourth rock. In the same manner this process may be continued to include the other rock-making elements, and, if the lines on the cross-section paper do not intersect at a common point, it is possible by inspection to determine the point which comes nearest to all of the lines, and thus we may determine what proportions of *X*, *Y*, and *Z* will make a combination which is as nearly like that of

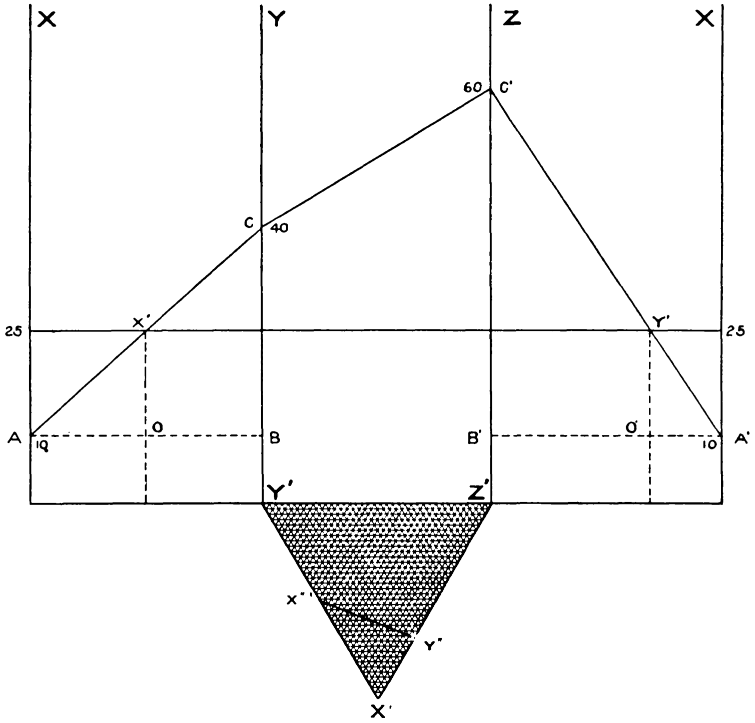

FIG. 5

a fourth rock as possible. An apparatus was constructed embodying the ideas shown in Fig. 2 and used in the solution of the problem. Silk threads were used for the edges and intersections of the planes, and to avoid confusion a different color was used for each component.

It was found, however, that more accurate results could be obtained by the following application of the principles involved in the apparatus. The three vertical planes are opened out flat, as shown in Fig. 4. The percentages are plotted as before, and intersections found at X' and Y' and projected down upon the base-line. The distances XY, YZ, and ZX correspond to the sides of the triangle, so the location of the points x and y is an easy matter. The problem admits of easy solution by this graphical method, but a very simple arithmetical solution is also possible which does away with the rather cumbersome details of a graphical solution and also admits of greater accuracy. In Fig. 5 the lines AB and $A'B'$ are drawn parallel to the base. In the left-hand side of the figure we have two similar triangles, ABC and AOx'. Hence $CB : AB :: x'O : AO$.

$$CB = 40 - 10 = 30\,, \qquad x'O = 25 - 10 = 15\,,$$

AB is equal in length to the sides of the triangle which is divided into 100 divisions, hence $AB = 100$.

Substituting the values in the above proportion, we have,

$$30 : 100 :: 15 : AO\,.$$

From which, $AO = 50$, and we see that the point x'' falls on the side $X'Y'$ of the triangle at a distance of 50 units from X'.

Considering the right-hand side of the figure, we have as before two similar triangles, $C'B'A'$ and $y'O'A'$, and we may write the following proportion,

$$C'B' : B'A' :: y'O' : O'A'\,,$$

$$C'B' = 60 - 10 = 50\,, \qquad y'O' = 25 - 10 = 15\,, \qquad B'A' = 100\,,$$

substituting values in the above proportion,

$$50 : 100 :: 15 : O'A'\,,$$

solving,

$$O'A' = 30\,.$$

We find that the point y'' falls on the side $X'Z'$ of the triangle at a distance of 30 units from X'.

RESULTS

The method of solution here described was applied to the four average analyses given in Table III, and the triangular diagram thus obtained is shown in Fig. 6. Since all the lines of the several elements in Fig. 6 do not intersect at a common point, some point must be selected which will give a minimum of discrepancies when the combination of the sediments is compared with the composition of the average crystalline rock. A rough idea of what these ratios are may be obtained from a general inspection of the diagram, and it is seen at once that a point as near to all of the lines as possible lies near the "Shale" corner of the triangle and a little to the left, indicating a large predominance of shale and more sandstone than limestone. The two elements which have the greatest bearing on the selection of the best ratio are calcium and silicon, since these two elements are more unevenly distributed among the three sedi-

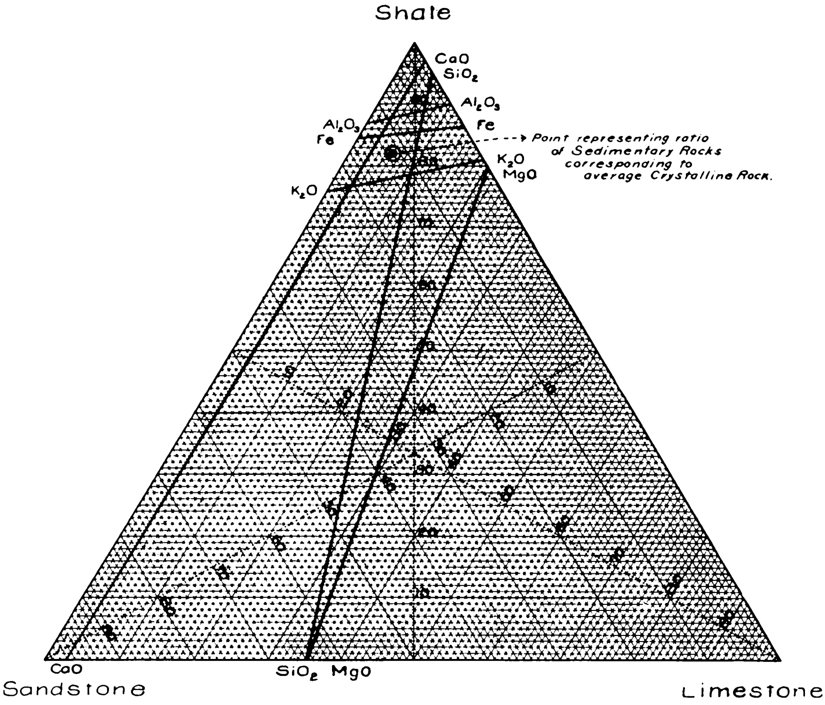
Shale
CaO
SiO₂
Al₂O₃
Fe
Point representing ratio of Sedimentary Rocks corresponding to average Crystalline Rock.
K₂O
MgO
Al₂O₃
Fe
K₂O
CaO
Sandstone
SiO₂ MgO
Limestone

FIG. 6

ments than any of the others, and any deviation from the best ratio will consequently produce greater discrepancies in calcium and silicon than in the elements which are more evenly distributed among the three sedimentary rocks. For this reason it is probable that the best point lies somewhere between the lime and silica lines. By referring to Table III it is seen that the shales contain more iron than either of the other classes of sediments, and hence a point above the iron line would indicate an excess of iron in the sediments and a point below it a deficiency. As we know that iron is segregated to a large extent in iron formations and ores, a deficiency is more probable than an excess, and the point evidently lies below the iron line. This throws it inside of the area bounded by the calcium, silica, iron, and potassa lines. A point at the center of this area gives a ratio of 82 parts shale, 12 parts sandstone, and 6 parts limestone, considering only such a part of the masses as is made up of the "derived" elements.

From Table II it is seen that the "derived" elements of the shales make up only 91.34 per cent. of the mass, of the sandstone only 95.30 per cent., and of limestone only 60.49 per cent. It is evident, then, that in the above ratio 82 represents only 91.34 per cent. of the total mass of the shales, 12 represents only 95.30 per cent. of the total mass of the sandstone, and 6 represents only 60.49 per cent. of the total mass of the limestone. If these figures are recalculated to take into account the entire mass of the sediments, we have as a ratio of shales, sandstone, and limestone, in even numbers, 80:11:9, respectively.

The relative abundance, then, of the three classes of sediments, as determined in the present investigation on the basis of average composition of crystalline rocks, is 80 parts shale, 11 parts sandstone, and 9 parts limestone.

The same process of solution was applied to a series of five average analyses of crystalline rocks,[1] ranging from acid to basic, and the same predominance of shale was observed in each case, ranging from 79 per cent. for acid rocks to 88 per cent. for the basic end of the series. This would seem to indicate that the redistribution of any crystalline rock results in a large predominance of shale in the resulting end-products. As would be expected, the ratio obtained from the average crystalline rock lies between those obtained for acid and for basic rocks; but it is noticed that the intermediate figure, 80 per cent., lies nearer the percentage of shale derived from acid rocks, 79 per cent., than that derived from basic rocks, 88 per cent. This indicates that in the group of analyses from which Clarke's average crystalline rock was obtained there was a considerable predominance of acid rock over basic rocks. This is in accord with the general opinion as to their relative importance.

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[1] Wright, *Tables of Igneous Rocks,* after Rosenbusch's classification.

DISCREPANCIES

In the following table the analyses of shales, sandstone, and limestone given in Table III have been combined in the ratios of 82:12:6, respectively, derived elements only being considered, and the resulting combination compared with the average crystalline rock.

TABLE IV

	Composition of Average Crystalline Rock	Average Analyses of Shales, Sandstone, and Limestone combined in the ratios of 82:12:6 respectively	Differences between the Composition of Av. Crystalline Rock and Comb. of Sediments
SiO_2	61.60	63.64	+2.04
Al_2O_3	15.47	14.71	−0.76
Fe	4.60	4.46	−0.13
MgO	4.18	2.90	−1.28
CaO	4.93	7.34	+2.41
Na_2O	3.50	1.29	−2.21
K_2O	3.02	3.12	+0.10

In the right-hand column the plus signs indicate an excess of that element in the sediments, and a minus sign indicates a deficiency.

While the sedimentary rocks form a very large proportion of the end-products of redistribution, it is evident that in considering only the sediments, as has been done in the solution of this problem, certain discrepancies may arise owing to the omission of the other end-products. These omitted end-products may account to a considerable extent for the discrepancies in Table IV. The most important of these omitted factors which admit at all of quantitative consideration are: mineral matter of the sea, the iron formations, and the residuary matter of the land. With a view of ascertaining to what extent the omission of these factors is responsible for the discrepancies obtained, certain suppositions have been made regarding the composition and abundance, based on the best evidence at hand. Van Hise[1] estimates the average thickness of the sediments over the continental areas as 2 kilometers, or about 6,000 feet, and their total mass as 675,000,000,000,000,000 metric tons. This estimate is well in accord with Salisbury's[2] estimate of one mile for the thickness of the sediments. The salts of the sea, computed as oxides from Dittmar's determination, amount to a total mass equal to about 3.5 per cent. of the total mass of the sediments, as estimated by Van Hise. It is assumed that the average thickness of the residual mantle over the continental areas is 60 feet, or 1 per cent. of the total thickness of the sediments, and as a rough approximation the thickness of the iron formations, if spread uniformly over the continents, is 60 feet, or 1 per cent. For the chemical composition of the residual material an average was taken of several analyses of residuary materials given by Merrill.[3] For the average composition of the iron formations an average was taken of several hundred analyses of Lake Superior iron formations, weighting the ratio of iron-carbonate to iron-silicate rocks in the proportion of seven of the former to three of the latter. It is not assumed that the figures for composition and abundance here employed represent very closely the facts, but they are sufficient to show, in a rather broad way, the effect which a consideration of these minor end-products would have on the discrepancies arising.

TABLE V

	Comp. of Sediments 82:12:6 100%	Mineral Matter of the Sea. Calculated 3.5% of Sediments	Av. Comp. of Residual Material. Assumed 1% of Sediments	Av. Comp. of Iron Formations. Assumed 1% of Sediments
SiO_2	63.64	00.00	61.45	51.40
Al_2O_3	14.71	00.00	21.94	1.25
Fe	4.46	00.00	8.25	28.50
MgO	2.90	12.31	0.99	5.38
CaO	7.34	3.32	0.98	3.82
Na_2O	1.29	81.76	0.81	0.00
K_2O	3.12	2.64	1.84	0.00

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[1] C. R. Van Hise, *A Treatise on Metamorphism*, Monograph No. 47, U. S. Geological Survey, 1904, p. 940.

[2] R. D. Salisbury, "Mineral Matter of the Sea," *Journal of Geology*, Vol. XIII, September-October, 1905.

[3] G. P. Merrill, *Rocks, Rock-Weathering, and Soils*, p. 306.

In the foregoing table are given the compositions of the end-products of redistribution and their relative abundance.

In order to find the composition of the sum of the end-products, it is necessary to combine the above analyses in the ratios of abundance. In Table VI the result of this calculation is given and compared with the composition of the average crystalline rock.

TABLE VI

	Composition of Average Crystalline Rock	Comp. of Sediments 82:12:6	Diff.	Comp. of Combined End-Products	Diff.
SiO_2	61.60	63.64	+2.04	61.39	−0.21
Al_2O_3	15.47	14.71	−0.76	14.16	−1.31
Fe	4.60	4.46	−0.13	4.58	−0.02
MgO	4.18	2.90	−1.28	3.21	−0.97
CaO	4.93	7.34	+2.41	7.11	+2.18
Na_2O	3.50	1.29	−2.21	3.99	+0.49
K_2O	3.02	3.12	+0.10	3.06	+0.04

By comparing the two columns of differences in Table VI, it is seen that the sum of the differences arising when only the sedimentary rocks are considered is reduced by more than half by including the other end-products in the combination. The discrepancy for each of the elements except one is made considerably smaller. In the case of alumina the difference is increased from 0.76 to 1.31, but for each of the other components the differences are decreased. This very evident improvement in discrepancies would seem strongly to indicate that the discrepancies are to a large extent due to not including in the consideration of the problem all of the end-products of redistribution. It is not improbable that with better figures for average composition and abundance the differences would be reduced still more.

The close accordance between the composition of the combination of sedimentaries and the original crystalline rock, and the relatively small corrections produced by taking into account the other end-products, argues the probable correctness of the ratios determined, and also shows the relative unimportance of the minor end-products of redistribution.

COMPARISON WITH OTHER ESTIMATES

Van Hise estimated the relative abundance of the three sedimentaries as 65 parts shale, 30 parts sandstone, and 5 parts limestone.

In the following table are listed the discrepancies arising under Van Hise's ratio of 65:30:5 and the differences encountered in the present investigation.

TABLE VII

Comparison of the Two Ratios

	Diff. under Ratio of 65:30:5	Diff. under Ratio of 80:11:9
SiO_2	+3.2470	+2.04
Al_2O_3	−3.6800	−0.76
Fe	−1.1490	−0.13
CaO	(no discrepancy)	+2.41
MgO	−2.2025	−1.28
Na_2O	−2.4985	−2.21
K_2O	−0.2925	+0.10

The differences are less for the ratio of 80:11:9 than for 65:30:5. Van Hise's choice of ratio was influenced by estimates of observed thickness and relative proportions, and not alone by analyses.

Another estimate of the relative importance of the three classes of sedimentary rocks is one made by Clarke.[1] In attempting to ascertain the average composition of the lithosphere, he estimates it to be made up of 95 per cent. of igneous rock, with 5 per cent. of sediments, and he assigns 4.0 per cent. to be shales, 0.75 per cent. to the sandstones, and 0.25 per cent. to the limestones. This is equivalent to a ratio of shales to sandstone to limestone of 80:15:5, which accords rather well with the results of the present discussion. Clarke obtained his results by assigning all the free quartz of the average crystalline rock to the production of sandstone and half of the calcium of the average crystalline rock to the formation of limestone. The figure for free quartz was obtained from petrographical descriptions of about 700 igneous rocks.

The results of the present investigation are also roughly in accord with the results obtained from measurement of materials carried by rivers, but so many factors enter into such comparison that it will not be discussed here.

It is hardly to be expected that the relative abundance of the principal sedimentaries determined from field observations should be in accord with the results obtained in the present investigation, which are based entirely on chemical evidence. This lack of accordance should not be interpreted as evidence that either of the ratios is incorrect. The figures obtained from field observations take into consideration only the present continental areas, and if it is assumed that they correctly represent the results of redistribution, it is also necessary to assume that the sedimentary formations at present on the continental areas constitute practically all of the redistributed material, or that sedimentation has been uniform over the earth's entire surface, in which case an average geological column for the continents would represent average sedimentation. The ratio based entirely on chemical evidence is not necessarily limited by the assumptions above mentioned, and for this reason it is believed that 80 per cent. shale, 11 per cent. sandstone, and 9 per cent. limestone is a better measure of the net results of redistribution than figures based on field evidence alone.

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[1] F. W. Clarke, "The Statistical Method in Chemical Geology," *Proceedings of the American Philosophical Society*, Vol. XLV (1906), p. 21.

SUMMARY AND CONCLUSIONS

The sedimentary rocks are ultimately derived from the igneous and crystalline rocks. The general average composition of the sedimentary rocks should equal the average composition of the igneous and crystalline rocks, when minor corrections are made for the materials not classed as sediments, but derived from the same source, such as the salts of the ocean and ore deposits. The three main classes of sediments constitute fully 97 per cent. of the end-products of the destruction of the igneous and crystalline rocks. It should be possible to combine these three great groups in such a manner as to make them yield an average composition similar to that of the parent rock.

It has been the purpose of this investigation to determine the proportion which most nearly accomplishes this result. A quantitative method of solution has been devised which permits of ready and accurate solution of the problem.

The result has been found to be 80 per cent. of shales, 11 per cent. of sandstones, and 9 per cent. of limestones.

This proportion accords with that derived from other methods of investigation in showing the striking dominance of shales in the sedimentary rocks.

The best available average analyses may not be correct, but the probable error, determined by noting the variations in the data available, is not so wide as to materially affect the result. It is believed that the proportion thus determined is entitled to more consideration than a proportion determined by measurement of field sections or of materials transported by rivers. If this proportion be not essentially correct, the best available average compositions vary essentially from the truth.

The small discrepancies between the composition of the parent rocks and the resultant principal groups of sedimentary rocks are found to be still further reduced when the relatively minute amounts of the minor end-products of the destruction of the parent rocks are taken into consideration.

The proportion of limestone determined (9 per cent. of the principal sedimentary rocks) is smaller than that obtained by measurement of geological sections. If the apparent difference is a real one—in other words, if the data which have entered into the two methods of calculation are reasonably correct—it may be concluded that there has been a concentration of limestone in the continental area. Whether this concentration is simply one of present areal distribution, the fragmental equivalents of the limestone at the present time being largely under the oceanic area, or whether the limestone has been uniformly concentrated through geological time in the upper part of the lithosphere, as has been held by certain writers, remains to be proved.

The work here outlined has been done in the metamorphic laboratory of the University of Wisconsin. I am greatly indebted to Dr. C. K. Leith for direction and criticism.